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Applications of satellite remote sensing for mapping and monitoring land surface processes in Western Australia

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Abstract

Visible and near infrared multi-spectral imagery of the earth from a civilian polar orbiting sun synchronous satellite first became available in 1971 and was first processed in Western Australia in 1974 for research into the broad area mapping of land cover types and geological structures. As other regions of the electromagnetic spectrum have become available on later satellites, applications have expanded. By the 1990s, repeat observations by similar sensors over many years were being used successfully to monitor changes in land surface conditions over large areas. The integrated, synoptic and temporal views of the changing earth is providing scientists with more complete information into land surface changes and associated processes. Regular monitoring by satellite is enabling future outcomes to be forecast and the community to be better involved in solutions. This is illustrated by increased community support for the management of bush fires in the Kimberley region following the introduction of routine satellite monitoring. Future opportunities for expanding such applications are discussed.

Introduction

Western Australia has a sparse population of only 1.7 million, managing a vast area of 253 million ha bounded by over 12,000 km of coastline. As a result there is an increasing use of satellite remote sensing to map, monitor, manage and explore the natural resources of Western Australia. Satellite observations complement aerial photography, where large area coverage is needed, natural features change rapidly or geographic information exists beyond the visible and near infrared parts of the electromagnetic spectrum.

Satellite usage is expanding with the number of hard copy high resolution satellite images produced by the Remote Sensing Services Branch, Department of Land Administration (RSS, DOLA) increasing from about 200 to 700 per year from 1984 to 1995 (Fig 1). The demand of the mineral exploration industry has probably caused a similar expansion in the private sector.

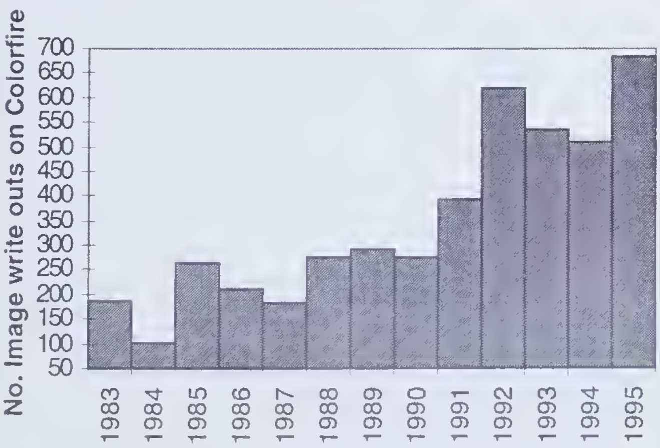

Figure 1. Number of high resolution satellite images produced as high quality photographic prints by Remote Sensing Services, DOLA.

Expanding demand for weather forecasting and for broad scale surveillance to monitor bush fires, drought and sea surface temperatures has contributed to significant growth in the reception and archiving of coarse resolution NOAA satellite data in Western Australia (Fig 2).

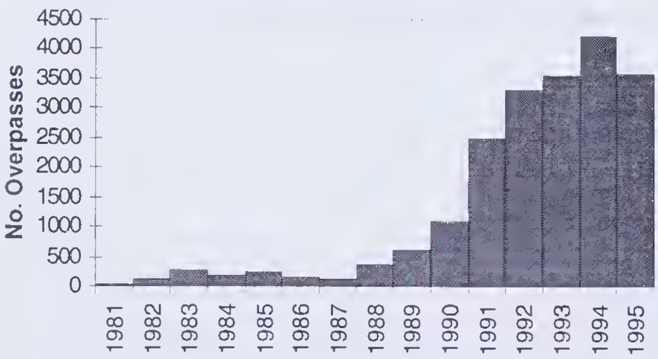

Figure 2. Number of overpasses of the NOAA satellite received and archived in Western Australia.

To outline how these satellite observations of the earth are impacting the quality of life in Westerna Australia, a general introduction to the principles of remote sensing is given, followed by a brief review of the application of these principles to monitoring and managing land surface processes. Complementary papers cover the applications of satellite remote sensing to oceanography (Pearce & Pattiaratchi 1997) and a bibliography of all publications on satellite remote sensing (research and development) conducted in Western Australia (Smith & Pearce 1997). Some basic texts on remote sensing are Richards (1986), Lillesand & Kiefer (1987), Legg (1992), Buitens & Clever (1993) and D'Souza *et al.* (1993).

Satellite remote sensing

The ability of people standing on land to observe the earth's surface is extremely confined by space and time, the oblique view angle, and the very narrow portion of the electromagnetic spectrum observed by the human eye. Earth observing satellites extend the human powers of observations by;

- continuous acquisition of data from the nadir view;
- regular revisit capabilities giving regular updates;
- broad regional and global coverage;
- wide coverage of the electromagnetic spectrum in the visible, infra-red, thermal and microwave bands;
- a range of spatial resolutions (from 100 km to 10 metres);
- ability to manipulate and enhance digital data;
- ability to combine satellite digital data with other digital data;
- cost effective coverage of regional, continental and global areas;
- map-accurate data;
- possibility of stereo viewing and digital elevation extraction; and
- large archive of historical data for monitoring changes.

Earth observations using satellites are limited by their fixed revisit times, the complexity of acquiring and processing the data and for the optical wavelengths by cloud cover.

The electromagnetic spectrum

Remote sensing measurements of the earth's surface are non-contact and non-invasive. They are based on measuring the interaction of the electromagnetic spectrum with the earth's surface. Passive remote sensing systems are the most common, where energy from the sun reaches the sensor by reflectance or emittance from the earth's surface. In active remote sensing systems the energy is provided by a radar or laser source from the remote sensing platform itself.

The electromagnetic spectrum includes a wide range of energy, from X-rays through visible light to radio waves. Only a portion of the electromagnetic spectrum can be used for satellite remote sensing due to limits set by the physical interaction of the radiation with the surface or the earth's atmosphere. When the wavelength of the radiation diminishes to the same order as the spacing between the molecules in the surface, the radiation is not reflected but is absorbed. In addition, depending on the wavelength, the energy from the surface being sensed is scattered or absorbed by the atmosphere on the way back to the sensor. This restricts remote sensing at the lower end of the visible wavelengths. The upper limit is set by the need to have reasonably detailed images of the earth therefore use of long wavelength radio waves is impractical. Having set the upper and lower limits, the useable electromagnetic spectrum is divided into six main sections by the absorption properties of the atmosphere (Fig 3).

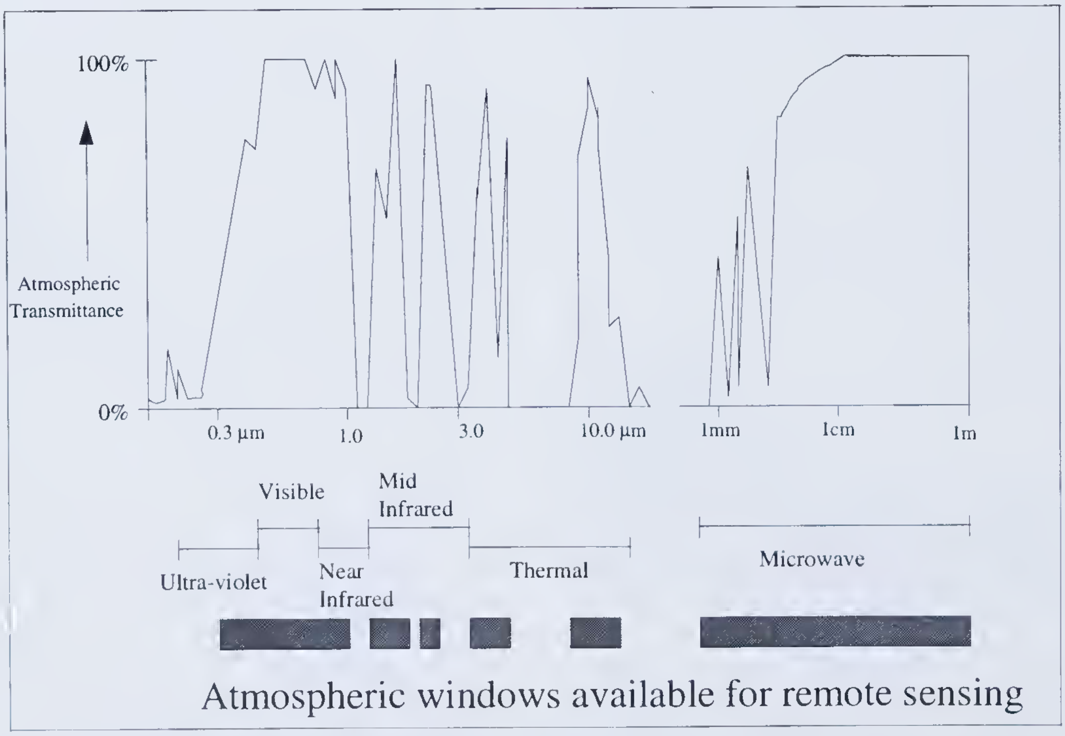

Figure 3. Portions of the electromagnetic spectrum used for remote sensing, showing the main subdivisions and atmospheric windows (modified from Legg 1992).

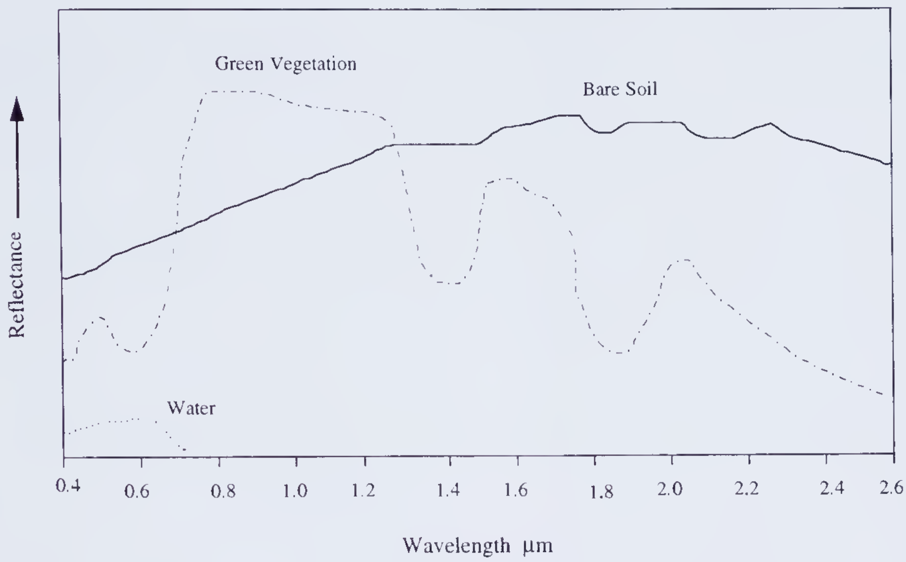

Figure 4. Typical reflectance spectra of dense green vegetation, soil and pure water (Modified from Legg 1992)

Ultraviolet. Atmospheric absorption is very strong in the ultra-violet, limiting satellite applications but applications are feasible using active airborne systems. World Geoscience Corporation in Western Australia operate an Airborne Laser Fluorescence (ALF) instrument at a wavelength of 0.266 μm for oil exploration. The spectra of the fluorescence enables oil films caused by seeps below the sea bed to be identified. Using the same principles, ALF could probably be used for the measurement of algal blooms caused by phytoplankton.

Visible. The largest atmospheric window and the highest amount of reflected solar energy is found in the visible wavelengths, and consequently it is the easiest to measure by satellite sensors in space. The first civilian earth observing satellite sensor, the Landsat Multispectral Scanner, had two of its four bands in the visible region with the third and fourth in the near infrared. Reflectance in the visible wavelength shows little spectral variation for rocks and soil (Fig 4) and is strongly affected by atmospheric scattering which causes a loss of dynamic range which limits contrast. Reflectance in the red part of the visible spectrum is useful for indicating the relative iron content of soils and all visible wavebands are useful for mapping surface geological structures (stratigraphy). Decreased reflectance in the visible part of the spectrum caused by chlorophyll absorption for photosynthesis is used for measurement of vegetation characteristics. Visible wavelengths penetrate water and are scattered back by suspended material and phytoplankton, whereas radiation in the infrared is almost totally absorbed by water (Fig 3). This enables visible wavelengths to be used for remote sensing studies of water quality and for the bathymetry of shallow coastal waters. However the energy levels are low and the dynamic range of sensors optimised for the land surface are often not well suited for remote sensing water characteristics unless the gain setting can be reset.

Near infrared. The near infrared (NIR) portion of the spectrum has similar energy to the visible part and consequently with appropriate filters can be recorded with the same type of sensor. Less absorption and scattering by the atmosphere occurs in the NIR, resulting in a higher dynamic range and imagery of good contrast.

Natural surfaces are rough, causing shadows. Consequently reflectance is a function of the sun and sensor view angles, giving rise to what is known as the bi-directional reflectance function (BDRF). In addition reflectance from vegetated surfaces with partial canopy cover is affected by the reflectance of the soil background. The NIR in combination with a visible waveband can be used to estimate green vegetation cover (Fig 5). To minimise the effects of season, sun angle and soil background on reflectance when measuring vegetation it is common to use a ratio such as the Simple Ratio (SR) between NIR and red (RED) reflectances;

SR= NIR/RED

or the Normalised Difference Vegetation Index;

NDVI = (NIR-RED)/(NIR+RED)
(Figure 5).

Using the visible and near infrared wavebands, the first civilian remote sensing satellite Landsat 1 was launched in 1971 into a polar sun-synchronous orbit at an altitude of about 900 km (Table 1). Orbiting the earth every 100 minutes at 27,000 km h^{-1}, the MSS sensor scanned a swath width of 185 km and covered the whole earth's surface after 233 orbits over 16 days at a resolution of 80 m. The analog signal was quantised to 6 bits (64 levels) and transferred to earth at a rate of 15 Mb s^{-1}. The spatial resolution of approximately 1 ha per pixel of Landsat MSS is relatively coarse compared with later satellites (compare Plate 1A with B,C,D).

Mid infrared. Use of the mid infrared wavelengths did not become possible until the launch of the Thematic Mapper (TM) sensor on board Landsat-4 (Table 2) in 1983. This spectral region has two atmospheric windows of high transmittance, one centred at 1.5 μm and the other at 2.2 μm (Fig 3). These wavebands are of importance in geological and vegetation studies. The relatively low level of reflected radiation at MIR wavelengths requires more sophisticated sensors and cooling to achieve high signal to noise. Landsat-TM also provided 30 m resolution

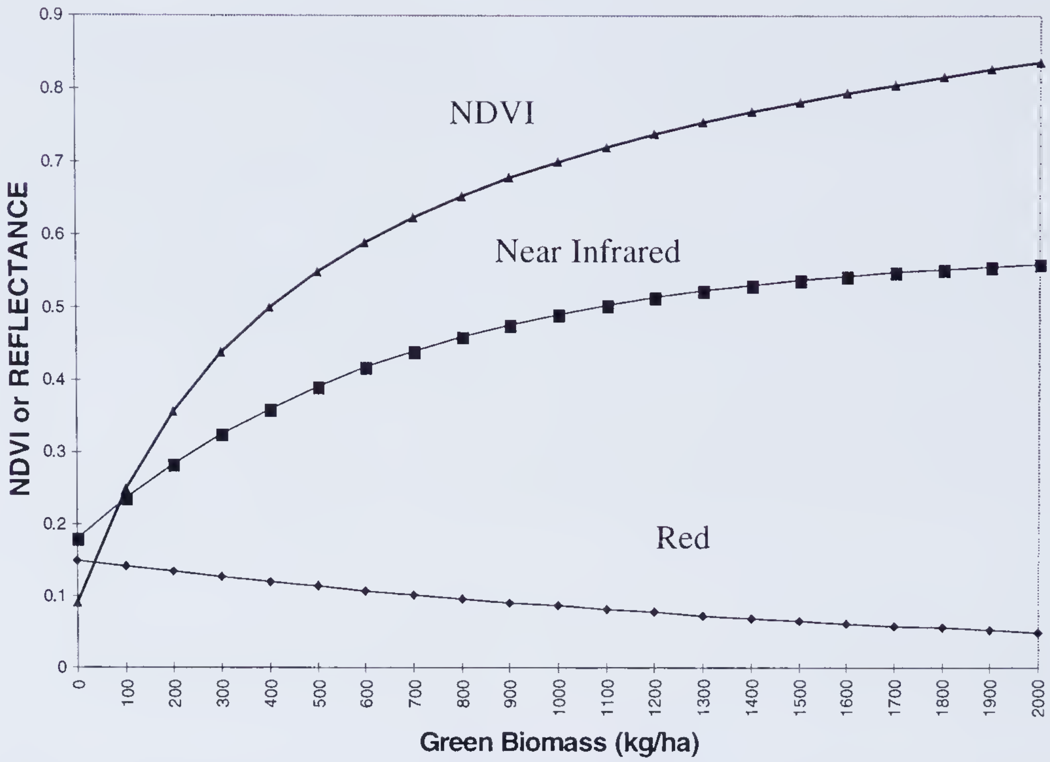

Figure 5. Hypothetical relationship between RED and NIR reflectances and the NDVI as a function of green biomass.

Table 1

Characteristics of Landsat Multi-Spectral Scanner (MSS).

Band	Wavelength (μm)	Description	Applications
1	0.5-0.6	Visible - green	Water studies
2	0.6-0.7	Visible - red	NDVI, water, soils
3	0.7-0.8	Red to Near Infrared	NDVI, topographic mapping
4	0.8-1.10	Near Infrared	NDVI, topographic mapping

Table 2

Characteristics of Landsat-TM.

Band	Wavelength (μm)	Waveband	Applications
1	0.45-0.52	Visible Blue	Water and urban studies
2	0.52-0.60	Visible Green	Water and urban studies
3	0.63-0.69	Visible Red	Water and vegetation studies
4	0.76-0.90	Near Infrared	Vegetation and topography
5	1.55-1.75	Mid Infrared	Vegetation, especially forestry
6	10.4-12.5	Thermal Infrared	Water, land surface temperatures and evapotranspiration
7	2.08-2.35	Mid Infrared	Soils and minerals

Table 3

Characteristics of the sensors on the SPOT satellite.

	Multispectral Mode (XS)	Panchromatic Mode (PAN)
Spectral Bands (μm)	0.50-0.59 0.61-0.68 0.79-0.89	0.51-0.73
Pixel size	20 m	10 m
Swath width	60 km	60 km
Repeat cycle	21 days	21 days
Steerable ± 27°	1-4 days revisit	1-4 days revisit

for all bands with 120m for the thermal infrared. This improvement in resolution can be seen by comparing Plate 1B with 1A from Landat-MSS. The Thematic Mapper was designed for mapping land cover themes and to improve precision the analogue signal was quantised to 8 bits (256 levels). The increased amount of data is transmitted to the earth at a rate of 85 Mb s^{-1}, which resulted in expensive X band reception facilities being provided by the Commonwealth Government at Alice Springs in 1987 for local reception. Landsat-TM has been the main satellite sensor used in high resolution remote sensing in Western Australia since 1987. Band 7 is in a region where the phyllosilicates such as clay minerals show absorption peaks. Therefore it was included at the insistence of geologists and has proved of value in lithological mapping and in the discrimination of clay-rich alteration zones. Band 5 is sensitive to the surface water content, therefore it is responsive to the amount and condition of vegetation. The broad width of these two wavebands restricts the amount of mineralogical information that can be derived. A multispectral capability in the MIR region is required to extract this information.

The high resolution Landsat-TM data was later exceeded by the 20 and 10 m resolutions of the French SPOT satellite launched in 1986 (Table 3; Plate 1C,D,). However, the higher cost and absence of routine coverage and lack of a mid infrared band has limited the application of SPOT multi-spectral data in Western Australia. The panchromatic data is often merged with Landsat-TM to improve the quality of the imagery for mapping surface features. SPOT with its steerable sensor enables stereo pairs to be acquired for digital elevation extraction. SPOT-4, due to be launched in 1997 (CEOS 1995), will have a mid-infrared band from 1.5-1.7 µm and a wide field of view sensor, named the VEGETATION sensor with a swath width of 2,200 km and resolution of 1 km. An image based on a general enhancement of Landsat-TM using bands 7,4 and 1 is commonly produced to assist geological mapping by the Geological Survey of Western Australia. An example of this enhancement from inland Australia is given in Plate 2.

Thermal infrared. This region includes two distinct atmospheric windows (Fig 3), separated by a strong atmospheric absorption zone caused by water vapour. Remote sensing in this region is similar to the mid infrared with low energy levels associated with emitted radiation. Special detectors, cooling and optics are required to get a high signal to noise ratio. Development of civilian space-borne thermal infrared sensors was driven by meteorologists who required measurements of sea surface and cloud top temperatures. The first polar orbiting satellite to provide thermal infrared sensors was the NOAA-Advanced Very High Resolution Radiometer (Table 4). It was launched in 1979 following a successful prototype first launched in 1974.

Designed for meteorological applications, NOAA-AVHRR has a wide field of view sensor covering a swath width of 2,800 km with a resolution of 1.1 km at nadir and transmitting at 665 kb s^{-1}. Bands 1 and 2 are used for detection of clouds, vegetation measurement and detecting firescars. Band 3 is used for detecting fires, as at this wavelength the sensor does not saturate at high temperatures and has the sensitivity to detect gas flares from the oil platforms on the NW shelf. Bands 4 and 5 provide cloud, land and sea surface temperature measurements. Based on differential absorption by the atmosphere, use of the two bands (4 and 5) can be used to empirically correct for atmospheric effects. The NOAA-AVHRR data has high radiometric resolution with 10 bit quantisation (1024 levels) and on-board black body calibration of the thermal sensors. Lack of on-board calibration of bands 1 and 2 has made accurate long term measures of vegetation difficult due to changes in sensor response over time. These changes occur when new NOAA satellites are launched, sensors age and overpass times drift later causing decreasing sun illumination angles.

NOAA-AVHRR is a American meteorological sensor whose data is free as part of a World Meteorological Agreement. Compared with Landsat-TM, NOAA-AVHRR provides high temporal resolution (daily *vs* 16 day coverage) but low spatial resolution (1 km *vs* 30 m), which keeps data handling manageable and makes economic local L-band reception (*ca*. $50,000) compared with X-band reception (*ca*. $2 million). This affordable capital cost has enabled operational use of NOAA-AVHRR to monitor seasonal vegetation growth, bush fire risk, fires, fire scar mapping and sea surface temperatures to be developed by RSS, DOLA. Operational monitoring of green vegetation cover is made using the NDVI (Plate 3) and achieved by combining successive NOAA overpasses over 14-16 day periods to produce cloud free images at the middle and end of each month.

The wavebands in the thermal infrared region contain significant geological information. Temperature differences between day and night often reveal buried geological features based on differences in specific heat. Differences in thermal emissivity are of value in lithological discrimination, but requires a multispectral capability that will be available on a proposed Japanese/American satellite.

Table 4

Characteristics and applications of the NOAA-AVHRR satellite sensor

Band	Wavelength (µm)	Waveband	Applications
1	0.58-0.68	visible	Surface features, cloud, vegetation, albedo
2	0.73-1.10	near infrared	Water, vegetation, firescars, albedo
3	3.55-3.93	thermal	Fires and volcanoes
4	10.5-11.3	thermal	Sea, land, cloud temperature and evaporation
5	11.5-12.5	thermal	Sea, land, cloud temperature and evaporation
Swath	2,800 km	Scan angle	± 55.4°, Resolution at nadir 1.1 km
Revisit	12 hours	Repeat cycle	9.2 days

Other **wide field of view sensors (WiFs).** The coarse resolution of the NOAA-AVHRR satellite restricts its use in agriculture as individual agricultural fields on the ground cannot be resolved. However WiFS sensors on the Russian RESURS-01 and Indian IRS-1C satellites (CEOS 1995) provide data in the visible and NIR wavebands at 170 m resolution that could be ideal for agricultural monitoring.

In addition to the above satellites which are polar orbiting and sun synchronous, Western Australia is observed by the Japanese Geosynchronous Meteorological Satellite (GMS-5) which is situated in a geostationary orbit at 140 E, 36,000 km above the equator. The 36,000 km distance compared with the 700 to 900 km of the polar orbiting satellites is required to maintain the satellite in orbit while orbiting at the same rate as the earth. The GMS satellite has a Visible (0.5-0.75 µm) and Infrared (10.5-12.5 µm) Spin Scan Radiometer (VISSR) which scans the earth from horizon to horizon every hour. The data is transmitted to Japan for processing before transmission to Melbourne, Australia for meteorological forecasting.

Microwave. The microwave portion of the spectrum is divided into a series of bands known as C band (6 cm), S band (13 cm), L band (25 cm) and P band (68 cm). Passive remote sensing of microwave emissions from the earth's surface by the Special Sensor Microwave/Imager (SSM/I) on the DMSP (Defence Military Satellite Program) is used for ice monitoring and precipitation measurement at spatial resolutions of 10-100 km. Active remote sensing systems based on synthetic aperture radar (SAR) are used to get higher resolutions of 10-30 m. The shorter microwave wavelengths are more strongly absorbed by natural material and the longer wavelengths penetrate further into the soil and overburden. The amount of energy scattered back to the sensor depends on the dielectric constant of the surface and its surface roughness. A major application of SAR is in tropical areas where dense cloud can prevent observations by optical sensors. In these areas the main applications appear to be mapping geological structures and changes in land cover such as deforestation. Several satellites have been launched with SAR sensors, the main ones being the Japanese Earth Resources Satellite (JERS-1) with L band launched in 1994, the European Earth Resources Satellite (ERS-1) with C band launched in 1991 and the commercial Canadian RADARSAT-1 with C band, HH polarisation and variable look angle launched in 1995. Projected future uses for SAR data are monitoring of floods, ice fields and oil spillage dispersed on the water surface. To date no significant applications in Western Australia have emerged for SAR data.

Other specialist radar sensors that might find oceanographic application in Western Australia are the altimeters and scatterometers. The altimeters on ERS-1 and TOPEX/POSEIDON measure deviations of the sea's surface height from the theoretical geoid to give estimation of the gravity field below the ocean and ocean currents on the surface. The wind scatterometer on ERS-1 records the change in radar backscatter of the sea caused by the wind close to the surface. Wind direction is derived from the orientation of the backscatter relative to the orientation of the pulse of microwave radiation transmitted by the scatterometer. These data are becoming available operationally and are being used in weather forecasting. NASA is using a wind scatterometer on Japan's Advanced Earth Observing Satellite (ADEOS) to send wind data every 2 hours to US weather forecasters (Gibbs 1996). Scatterometer data can also be used to measure vegetation types (Long & Hardin 1994).

Developments using airborne sensors

The development and application of satellite sensors has been assisted by experience gained with airborne multispectral scanners such as the GEOSCAN which was built locally in Western Australia and widely used in mineral exploration and environmental monitoring. At a lower cost, a Digital Multi-Spectral Video (DMSV) which uses four CCD video cameras with filters giving wavebands typical of Landsat MSS for vegetation and water measurements has been developed locally. Demonstrating the potential value of SAR data from satellite, NASA has flown the Airborne Synthetic Airborne Radar (AIRSAR) instrument in Western Australia for experimental purposes. This instrument has P, L and C-band with four different polarisations (HH, HV, VH and VV) and a duplicate set of sensors with L and C-bands at VV polarisation (TOPSAR) for interferometry measurement of elevation. This multiple range of frequencies and polarisations will become available on later satellite SAR sensors.

Use of satellite data for surface geological mapping complements a range of ground penetrating geophysical airborne instruments that are flown to map various below ground geological features. These instruments measure magnetics, conductivity (electro-magnetics) and gamma ray emissions (radiometrics). To aid geologic interpretation of the distribution of weathering products in the landscape, it is common to merge airborne radiometric and Landsat-TM satellite data.

Sensors of the future

The application of satellite remote sensing is still young. Over the next 15 years another 80 missions are planned with over 200 sensors proposed (CEOS 1995). Capturing the benefits from these sensors will be a challenge to researchers and applications scientists. Developments in microelectronics creates new sensors, lower weight satellites, faster communications and more powerful computers to process the data. Spatial resolution will increase from 10 m to <1 m creating digital photogrammetric applications. Hyperspectral data (*e.g.* 256 spectral bands with 0.08 µm bandwidth in the optical wavelengths) will increase spectral resolution for enhanced applications in mineral detection and environmental monitoring. New radar satellites will have a wider range of microwave frequencies and polarisations. Without loss of spatial resolution, temporal resolution will be increased through the use of constellations of earth observing satellites to enable the monitoring of dynamic changes such as crop growth in agricultural fields and grass growth in rangelands.

Capturing the economic and environmental benefits of these sensors for Western Australia will require a continued growth in local research and development. Timely acquisition for monitoring may require the establishment of a local X-band reception capability.

Development of terrestrial applications of remote sensing

Given these technological opportunities, significant initiatives by Commonwealth and State Government agencies have helped develop applications of satellite remote sensing in Western Australia (Smith & Pearce 1997). The bibliography complied by Smith & Pearce (1997) indicates that the first recorded publication on terrestrial applications was by Honey *et al.* (1978) using Landsat MSS, for the classification of wetlands on the Swan coastal plain. This classification was based on the spectral differences of wetlands from the surrounding land. The next publication (Houghton 1979) reports the coordination of remote sensing activities which has been an important feature of the successful development of remote sensing in Western Australia where resources for the development of this new technology have been limited. Development of marine applications is covered by Pearce & Pattiaratchi (1997).

Landcover type

The bibliography records that landcover types mapped over the following 16 years using Landsat MSS and TM were mangroves (Honey & Hick 1981), tropical rainforests in the Kimberley (Kay *et al.* 1990), areas of remnant native vegetation in the agricultural area (Campbell & Wallace 1989), forest cover of water catchments (Wyllie & Barile 1990) and areas of gravel suitable for road building (Wyllie *et al.* 1992). The mapping soon extended to geological structures using Landsat data (Smith & Green 1979) and subsequently NOAA-AVHRR (Honey & Tapley 1987; Tapley & Wilson 1986). There are many other significant applications to geology and exploration that are not covered in this review. The significance of this geological use is indicated by the fact that about 60% of all satellite data purchased in Western Australia is used for geological mapping or exploration. The outcomes appear not in scientific publications but as improved geological maps from the Western Australian Geological Survey and the finding of new mineral deposits by the exploration industry.

High resolution satellite imagery is periodically ordered by State agencies such as the Ministry of Planning, Department of Environmental Planning, Ministry of Transport, Department of Agriculture, Department of Conservation and Land Management and the Bush Fires Board for mapping urban development, status of wetlands and new roads, status of National Parks and bush fire assessment.

Land degradation

Degradation has been the subject of a number of studies using classification or visual interpretation to map areas of agriculture affected by wind erosion (Carter & Houghton 1981), salinity (Currey *et al.* 1981; Furby 1994; Wheaton 1992; Wheaton *et al.* 1992) and waterlogging (Wallace & Wheaton 1990; McFarlane *et al.* 1992) and areas of forest affected by dieback *Phytophthera cinnamoni* (Behn & Campbell 1992) and insect damage (Behn *et al.* 1990). The success of the spectral technique for mapping salinity has been recently enhanced by integration of satellite data with information derived from digital elevation data (Caccetta *et al.* 1995a,b; Plate 4). Following the demonstration of the potential, the State Government plans to adopt this technology to map the extent of salinity and condition of remnant vegetation in the agricultural area to help combat these major environmental problems.

The low albedo of native vegetation compared with agricultural crops (Smith *et al.* 1992) means that spectral information in the visible, near infrared and mid infrared regions is ideally suited for mapping areas of remnant native vegetation in agricultural areas and water catchments (Wallace & Furby 1994). The first comprehensive mapping of changes in the area of native vegetation in the agricultural area from 1991-1991 using Landsat-TM data is currently being attempted. This work is being contracted by the Commonwealth Bureau of Resource Sciences to establish the sources of CO_2 causing the greenhouse effect. Water quality associated with land degradation has been successfully measured using spectral measures of water colour (Pattiaratchi *et al.* 1991, 1992, 1994). Such measures are dependent on relatively smooth water to avoid the sunglint and turbidity caused by rough water. Sequential measures of sea surface water temperatures have been used to estimate currents in the Indian Ocean (McAtee 1992).

Using the Coastal Zone Colour Scanner (CZCS) on the experimental Nimbus-7 satellite, measurement of ocean chlorophyll associated with land degradation has been demonstratedd by Pattiaratchi *et al.* (1990). Future use of satellite measures of ocean chlorophyll in Western Australia awaits the anticipated launch of the Sea viewing Wide Field-of-view Sensor (SeaWiFS) in 1997 (Davies *et al.* 1994). More detailed discussions of these applications in the marine environment is contained in Pearce & Pattiaratchi (1997).

Atmosphere

Operational use has been made of satellites in Western Australia to measure atmospheric conditions. The TOVS (Tiros Operational Vertical Sounder), a set of three instruments on the NOAA satellite, is used by the Bureau of Meteorology to measure longwave emittance in a large number of wavebands for a 60 km foot print. From the solution of the radiative transfer equation, the vertical distribution of temperature and moisture is derived for use in operational weather forecasts by the Bureau of Meteorology. Lynch & Marsden (1992) have also derived estimates of aerosol optical depths from NOAA-AVHRR data.

NOAA-AVHRR also offers opportunity to measure cloud top temperatures and cloud climatology associated with changes in vegetation cover. For example, clearing of native vegetation and replacement by annual agricultural species has been observed to cause a decrease in formation of convective clouds (Lyons *et al.* 1993; Lyons *et al.* 1996). Further study of this process is occurring at Murdoch University using NOAA-AVHRR data. In Africa the duration of cloud top temperatures below a certain threshold determined from the European geosynchronous meteorological satellite is used to forecast the spatial distribution of rainfall in areas where rain gauges are sparse.

Land surface processes

Satellite imagery is used periodically by Remote Sensing Services, Department of Land Administration (RSS, DOLA) to analyse the impact of flooding events on rail, road and pipeline links to assist in assessing the suitability of these engineering structures as they cross the landscape. These images have been enhanced using digital elevation models to create 3D perspectives of the distribution of flood waters. These 3D perspectives are also widely sought after as an aid to geological interpretation (Davison 1992). The possibility of digital elevation extraction using stereo pairs from the SPOT satellite also exists but has not been used in Western Australia, where elevation information from aerial photography is readily available.

Energy fluxes at the land surface over large areas can be studied by using NOAA-AVHRR data to help solve the energy balance equation of the surface. This approach has been used to study the impact of large scale clearing of native vegetation in south western Australia on sensible and latent heat fluxes (Lyons *et al.* 1993, 1996). It was found that the higher albedo following clearing of land for agriculture caused lower sensible heat flux. This lower sensible heat flux causes reduced convection indicating a possible mechanism for the observed 20 to 30 % decline in rainfall that has followed large scale land clearing in south-western Australia.

Monitoring and forecasting land cover changes:

Accurate monitoring is a powerful information tool for increasing public awareness to achieve desired management outcomes. Repeat observations by satellite sensors offer the possibility of monitoring changes in key environmental variables on a routine basis. Areas of bush fires, drought, salinisation, wind erosion, poor agricultural productivity, remnant native vegetation and plantations are examples of changes that can now be routinely monitored. From such changes the processes can be modelled, future outcomes forecast, public support enrolled and better management decisions taken. This forecasting application has been demonstrated by Caccetta *et al.* (1995) for salinity, Smith *et al.* (1995) for wheat yields, and Lyons *et al.* (1996) for the impact of clearing on rainfall.

An example of monitoring and forecasting environmental change is the operational measurement of variations in green vegetation cover at 14 to 16 day intervals across Western Australia using the NDVI from NOAA-AVHRR (Plate 3). Seasonal vegetation growth determines the outcome of later events such as fuel load build up

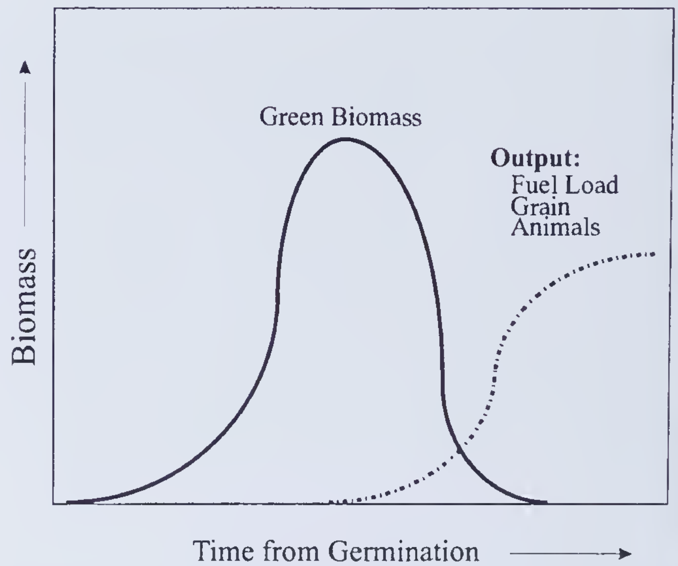

Figure 6. The hypothetical relationship between the seasonal growth of vegetative biomass of annual species and the resultant output of grain, animal products and fuel load.

that sustain fires, drought caused by feed deficit, crop yields and production of grazing animal, which can therefore be forecast (Fig 6).

Monitoring of variations in seasonal vegetation growth of winter-growing Mediterranean annual species in the agricultural area of south-western Australia from NOAA-AVHRR data is shown in Figure 7. Every season, following the winter rains, there is a pronounced period of vegetation growth marked by a rise in the NDVI about May/June rising to a peak in September/ October (Fig 7). There is then a decline as the annual pastures and crops senesce.

The variations in the peak NDVI across the grain belt of Western Australia are closely related to the grain yield of wheat (Fig 8). This close relationship between biomass around anthesis estimated by the NDVI in mid season and final grain yield can be used to forecast wheat yields in December (Fig 8). Similar relationships between paddocks using NDVI calculated from Landsat-TM and SPOT XS data and wheat yields exist and are used to produce yield maps of farmer's fields (Stovold *et al.* 1996).

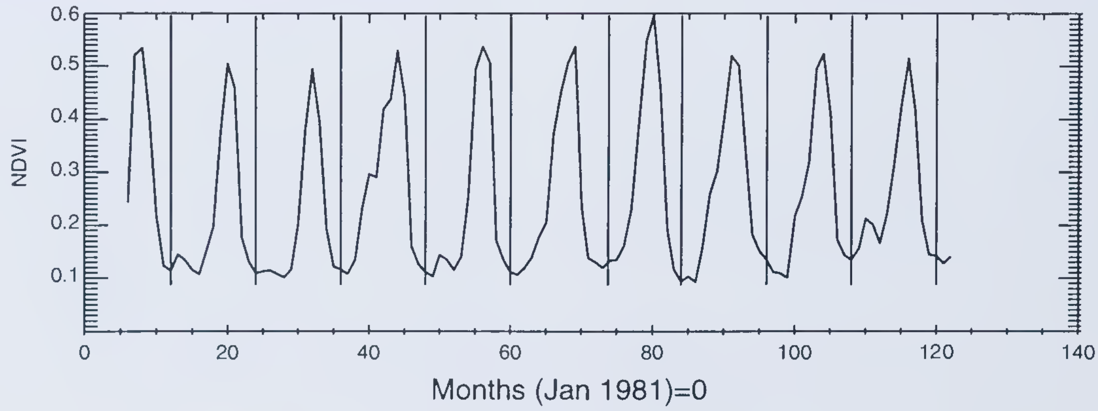

Figure 7. Monthly NDVI time series from NOAA Global Area Coverage data from 1981-91 for a location in the central grainbelt of Western Australia.

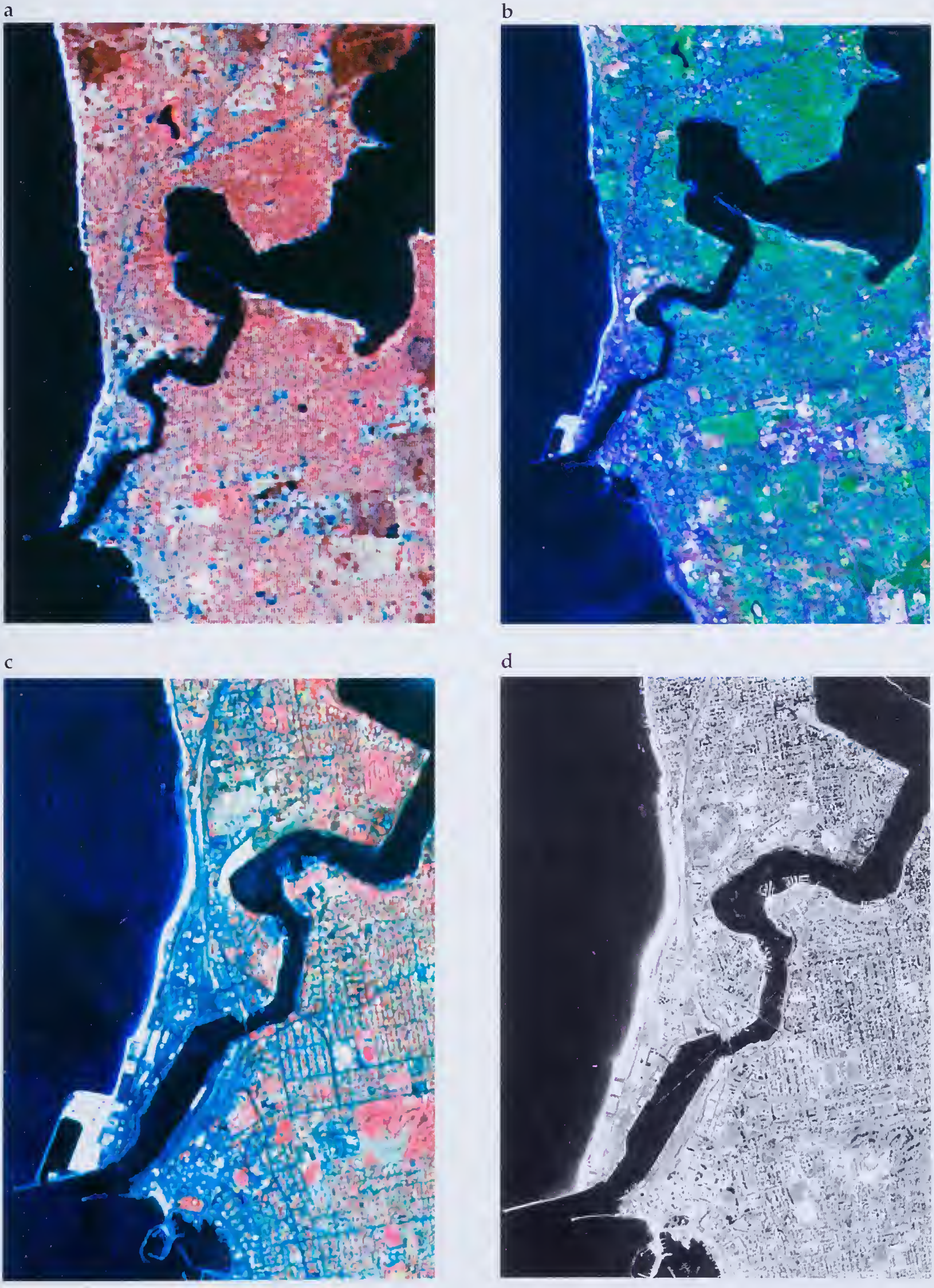

Plate 1A,B,C,D. Comparison of images of the Port of Fremantle and the Swan River, Western Australia to indicate the change in spatial resolution from 1971 to 1986: (a) Landsat MSS (80m) (b) Landsat-TM (30m), (c) SPOT XS (20m) and (d) SPOT PAN (10m).

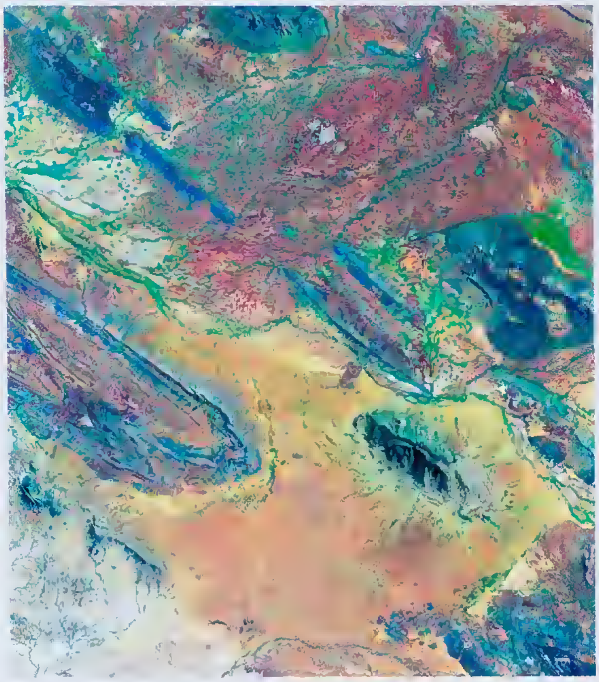

Plate 2. An image map of sheet 2249 of the Australian 1:100,000 topographic series covering Mt Augustus produced from Landsat-TM bands 7,4,1 (Red, Green and Blue) produced for use in geological mapping. Mt Augustus, or *Burringurrah* as it is known to the Wadjari Aboriginal people, is about 800 km north of Perth. It is one of the most spectacular solitary peaks in the world. It rises 717 metres above the surrounding plain and is about 8 km long. The dark coloured peak is evident in the lower right hand quarter of the image

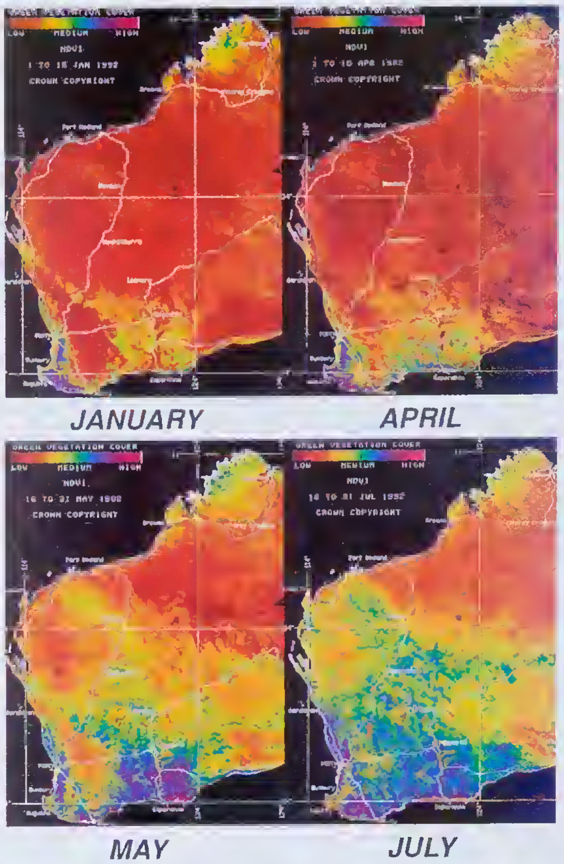

Plate 3. A sequence of images of green vegetation cover of Western Australia based on the NDVI derived from successive overpasses of the NOAA-AVHRR sensor over a 14 to 15 day period using maximum value compositing. The area covered is some 252 million ha.

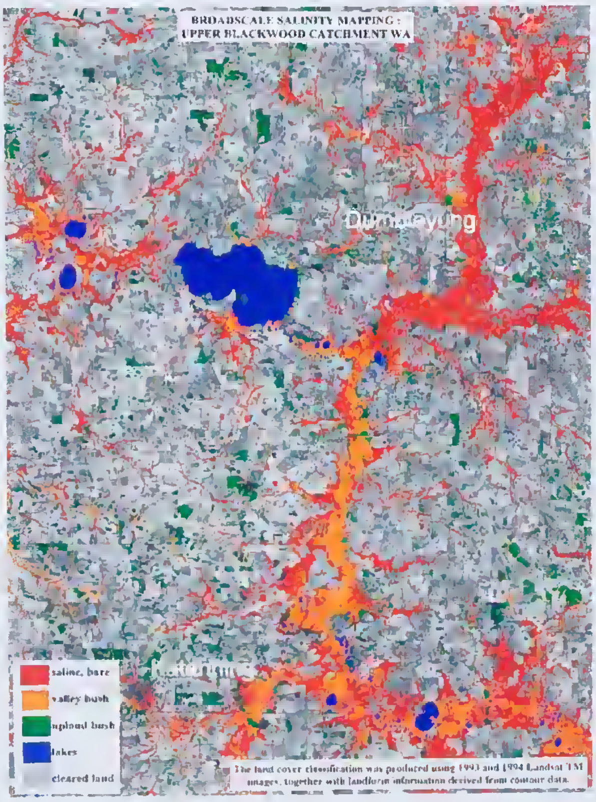

Plate 4. A typical application of Landsat-TM is to map areas of salinisation by classification. This example is an area of the grain belt of Western Australia, 200 km south east of Perth covering an area of about 2,000 km^2. The technique uses two successive Landsat-TM images during the winter period of crop growth and digital elevation data to classify areas affected by salinity.

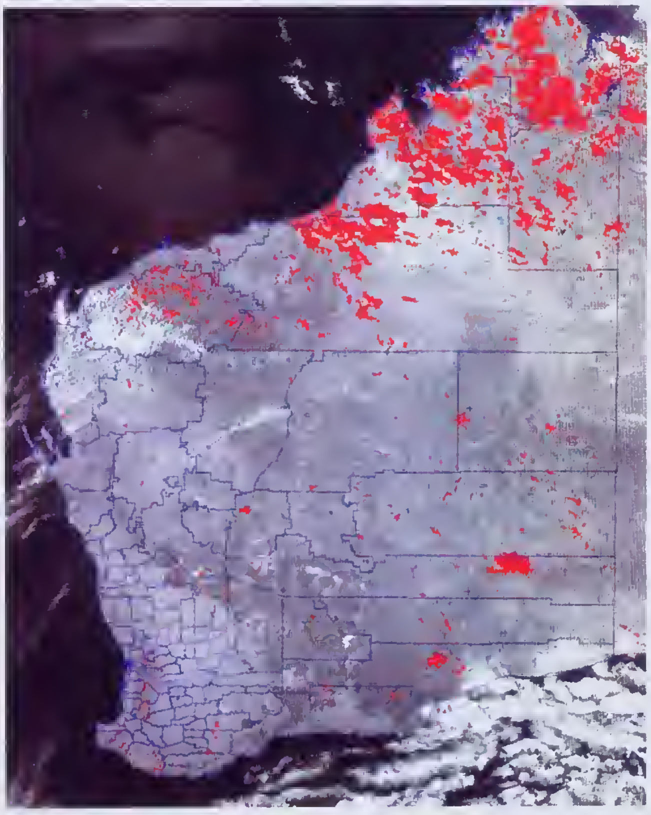

Plate 5. Areas burnt by fires between April 1995 and March 1996 mapped from the NOAA-AVHRR sensor at 10 day intervals.

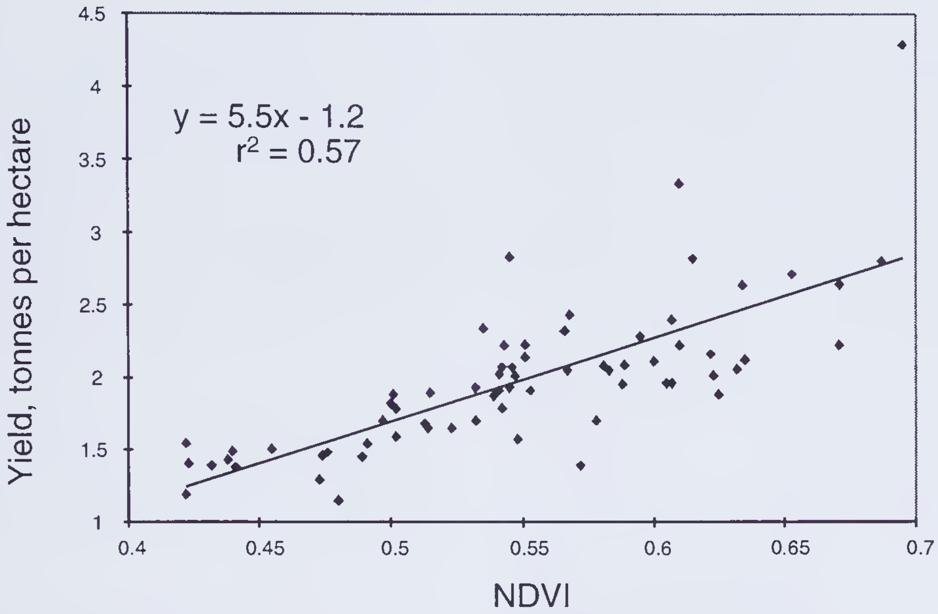

Figure 8. Relationship between the mean NDVI in September 1995 from NOAA-AVHRR data and wheat yield (tonnes ha^{-1}) of 68 local government areas in the Western Australian grain belt (Smith *et al.* 1995).

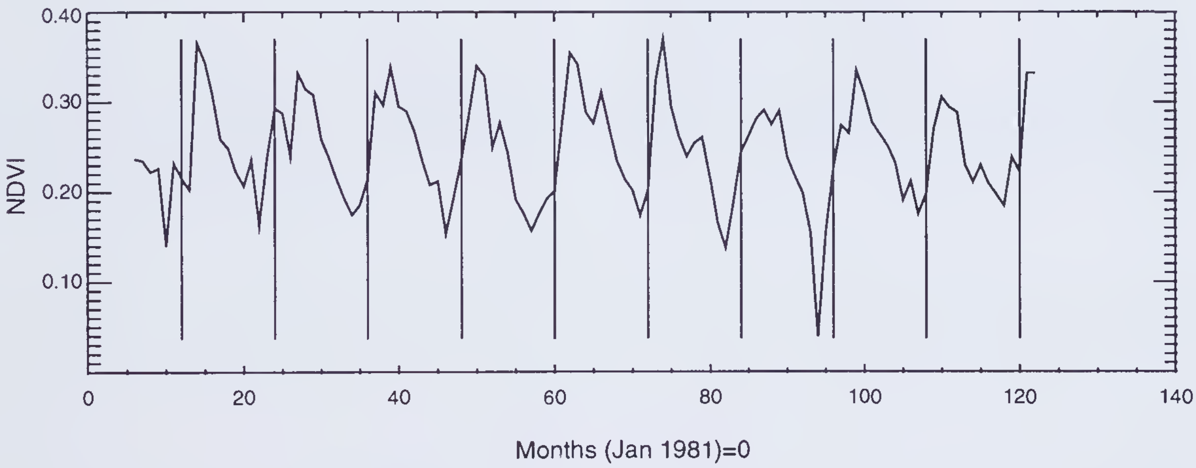

Figure 9. Monthly NDVI time series from NOAA-AVHRR from 1981-91 for the Kimberley area of north-western Australia (note the change in scale from Fig 8).

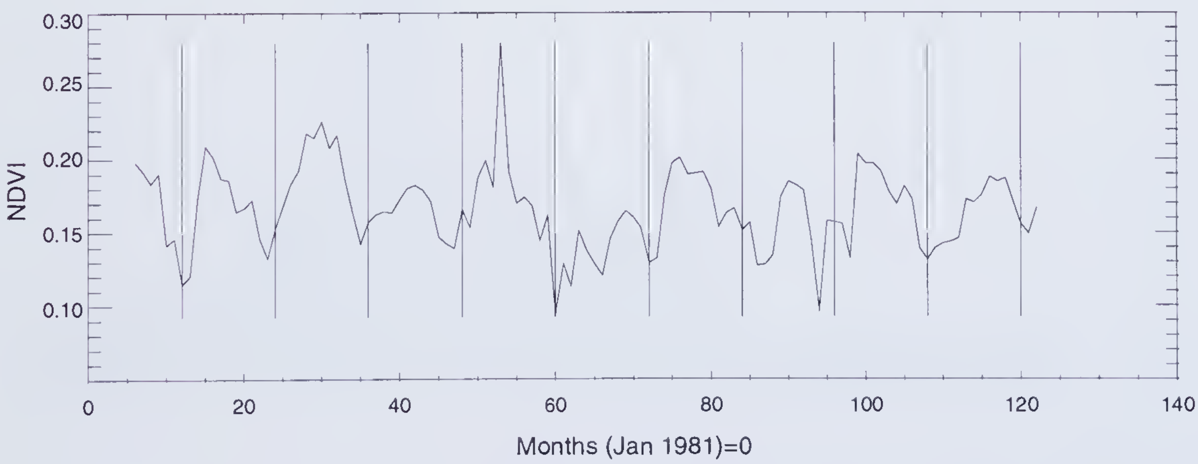

Figure 10. NDVI time series from NOAA-AVHRR GAC data from the central desert area of Western Australia (note the change in scale from Figs 8 and 9).

In north western Australia, which experiences summer monsoonal rains, there is a similar pattern of seasonal vegetation growth with a lower range in NDVI beginning in December and ceasing in about April (Fig 9). The seasonal distribution of this information is used by the Bush Fires Board in Western Australia to monitor the rapid build up in fuel load which provides the basis for extensive bush fires ignited by a variety of natural and human causes. It is also used to plan controlled burning by the Bush Fires Board.

In comparison, the seasonal growth in the inland areas of Western Australia, with lower and more variable rainfall, is much less and more varied (Fig 10). Comparison of current seasonal trends in the NDVI with the long term trend has been used to map areas affected by drought in pastoral areas (Cridland *et al.* 1994).

Near real-time mapping of bush fires for the Bush Fires Board covering the whole of Western Australia has been implemented (Smith *et al.* 1996; Plate 5). The outcome of this fire monitoring in 1995/96 was the detection

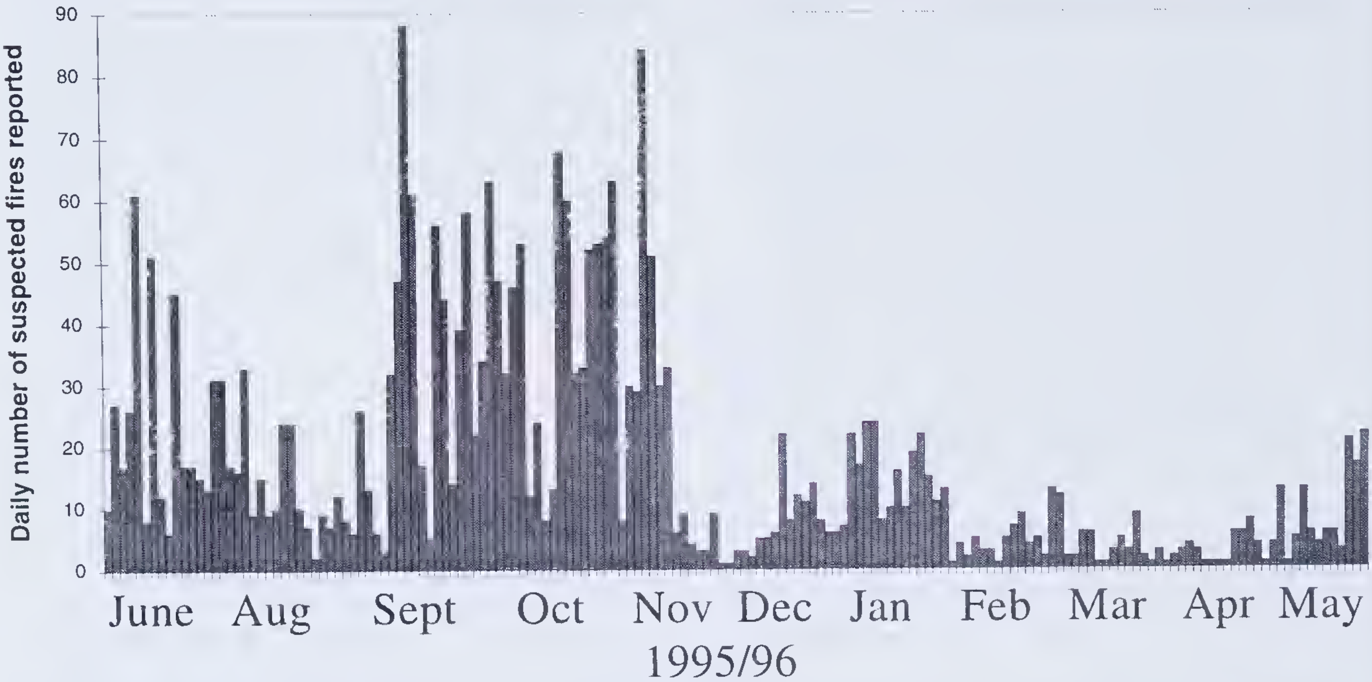

Figure 11. Daily number of suspected bushfires in Western Australia detected from the NOAA-AVHRR satellite in 1995/96 by Remote Sensing Services, DOLA, whose location was reported to the Bush Fires Board within 4 hours of the overpass.

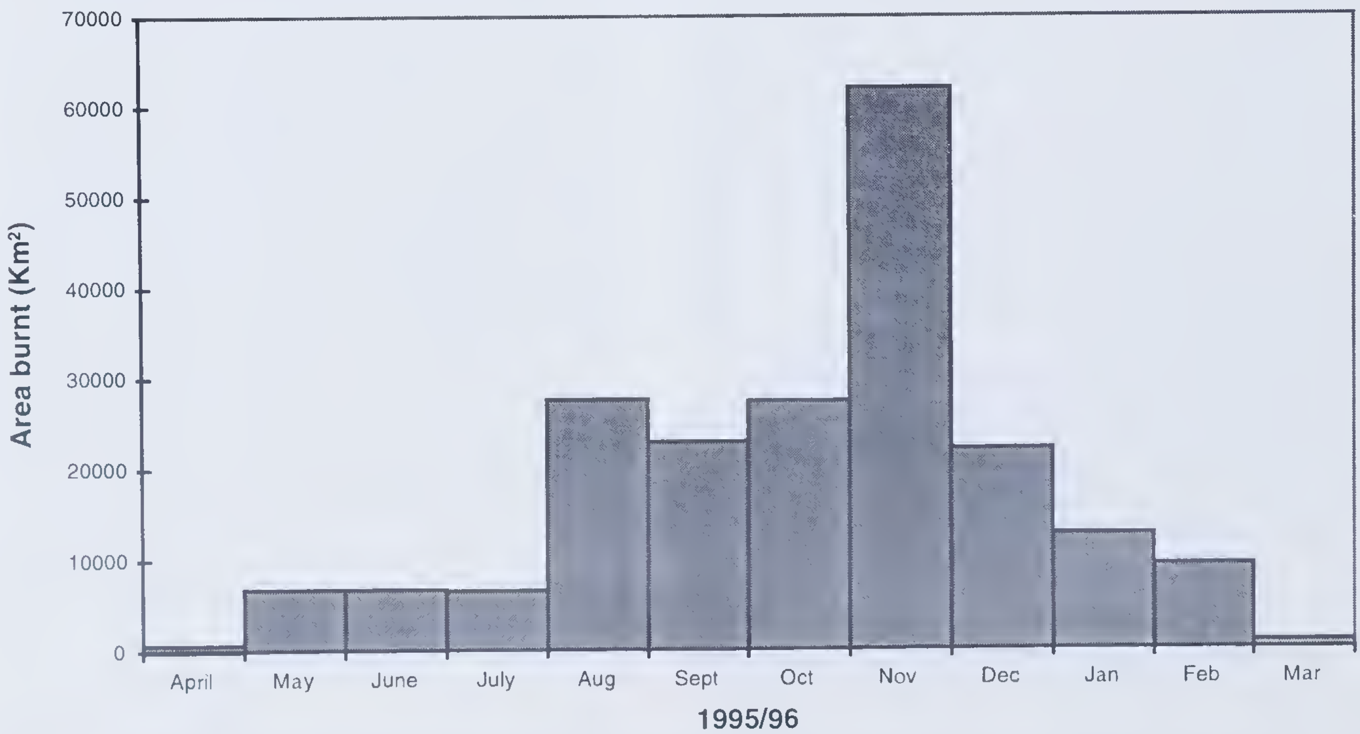

Figure 12. Area burnt by bushfires in Western Australia that was mapped from NOAA-AVHRR in 1995/96. Total area burnt is estimated at 20.6 million ha.

of over 2,700 bush fires reported to the Bush Fires Board by fax or internet within 4 hours of the data being received (Fig 11). The mapping indicated a total area burnt of about 20.6 million hectares, most in the north west of the State (Fig 12). This is the first time that such comprehensive information on bushfires has been available and is an example of the type of spatial and temporal geographic information that can now be made available from satellites.

The availability of these data on a routine basis in near real-time to the Bush Fires Board of Western Australia has had a significant impact on enrolling community support for the management of Bush Fires in the Kimberley. It has transformed a "we can do nothing" attitude to a "we can do". Instead of chasing bush fires, the Bush Fires Board reports that land managers are now able to see ahead and plan strategies that will provide more effective control and less risk.

Conclusions

Earth observations by satellite offers significant potential for using space to improve exploration and the management of Western Australia's renewable resources. After 20 years of research, techniques have progressed from the photo-interpretation of satellite imagery to the routine extraction of geographic information using automatic methods. The knowledge base for the much wider use of this technology has been created, but the challenge of widespread adoption remains.

Land cover types can be mapped and the spatial variability of certain key land surface processes measured from space. Monitoring changes in area of remnant native vegetation and salinity in the agricultural area using high resolution data, is now possible. Public access to such information provides a powerful means for Government to raise public awareness and support for extending the area of native vegetation. Application of NOAA-AVHRR to routinely monitor bush fires over West Australian has demonstrated that such systematic use of satellite information would improve the ability of Government to implement policies to combat environmental degradation.

Increased spatial, spectral and temporal resolution of future sensors will expand the opportunities for exploration and monitoring the environment. Ongoing Government investment into methods for capturing information from these new sensors, including X band reception capability in Western Australia for timely coverage may be required. Continued CSIRO research to generate the core knowledge to enable geographic information to be extracted from these new forms of data will be important.

The advent of ocean colour sensors and radar altimeters and radar scatterometers as a complement to existing sea surface temperature data will greatly enhance our ability to manage Western Australia's surrounding oceans and coastal zone.

We are at the beginning of the next era in earth observations from space which could give rise to many new applications of satellite remote sensing to the successful exploration and the management of the renewable resources of Western Australia.

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